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Relativistic bound states in the “top”-mass region: vector and new scalar mesons

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Abstract

A second order Lagrangian, which resolves the problem of the infrared divergency of the Standard Model of particle physics, has been used to describe relativistic $q\bar{q}$ bound states in the “top”-mass region. A consistent description is obtained by assuming massless elementary fermions (quantons). Interestingly, a vector (1^-) state is found with a mass of ~ 91 GeV, which is identified with $Z(91.2 \text{ GeV})$ (viewed as gauge boson of the weak interaction). A second vector state is obtained with a mass of about 375 GeV, consistent with the “top”-state ($t\bar{t}$ in the quark model), which decays into two “single-top” states with masses of about 175 GeV.

Two scalar (0^+) states are found with masses of 33 GeV and 126 GeV. Interestingly, the latter has the same mass as a scalar state discovered recently in high statistics ATLAS and CDF data, the other one should be found in high energy experiments. This can be taken as test of the consistency of the present model, in which an interpretation of the 126 GeV state as Higgs-boson is excluded.

PACS/ keywords: 11.15.-q, 12.40.-y, 14.40.-n/ Bound state description of $q\bar{q}$ states in the top-mass region. 1^- and 0^+ states obtained, one 1^- states identified with $Z(91.2 \text{ GeV})$. Two 0^+ states found with masses of 33 GeV and 126 GeV, the latter with the same mass as a scalar state discovered recently. A relation to Higgs-fields is excluded.

In the study of the most fundamental systems of nature hadron and weak interaction physics play a particularly important role. One of the biggest achievements of particle physics is the establishment of different favour systems [1]. The observation of states in the “top”-mass region (with a mass significantly larger than the bottomonium-system) is of

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particular interest, since in addition to “top” states ($t\bar{t}$ states in the quark picture) this is the mass region of the heavy bosons of the weak interaction, but also of the Higgs-boson and supersymmetric particles predicted in extensions of the Standard Model of particle physics (SM).

A severe problem of the SM is that divergencies appear for momenta $q \rightarrow 0$ and $q \rightarrow \infty$. That for $q \rightarrow \infty$ can be overcome by renormalisation techniques, but the infrared divergency for $q \rightarrow 0$ does not allow to construct hadrons of finite size as observed experimentally. So far, only in the lattice approach finite hadrons could be simulated. However, this rather complex empirical method does not allow to identify the detailed mechanisms, which lead to hadron binding.

Recently, a second order extension of the SM Lagrangian by two boson fields has been developed [2], in which the infrared divergency of the SM disappears. Such a Lagrangian yields solutions only, if the time component of both boson fields is the same, leading naturally to a non-relativistic system, for which bound state potentials can be deduced. Importantly, in this formalism all parameters needed are constrained by self-consistency conditions, so that a description without free parameters is obtained. By applying this approach to hadron structure surprising results [2] are obtained: To get a fully consistent description of different $q\bar{q}$ flavour systems, the assumption of massless² elementary fermions (quantons) is needed. Further, the confinement of hadrons is obtained in an Abelian form of the Lagrangian, indicating that this important mechanism is not due to the colour structure of QCD but rather a characteristic property of relativistic bound states.

The Lagrangian is written in the form

$$\mathcal{L} = \frac{1}{\tilde{m}^2} \bar{\Psi} i\gamma_\mu D^\mu D_\nu D^\nu \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} , \quad (1)$$

where \tilde{m} is the reduced mass and Ψ a two-component massless fermion (quanton, q) field $\Psi = (\Psi^+ \Psi^o)$ and $\bar{\Psi} = (\Psi^- \bar{\Psi}^o)$ with charged and neutral part. Vector boson fields A_μ are contained in the covariant derivatives $D_\mu = \partial_\mu - igA_\mu$ and the Abelian field strength tensor $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$. Only couplings to the charge ($g = g_c$) and spin ($g = g_s$) of quantons are considered. Importantly, by using this more complex second order Lagrangian, the infrared divergency problem of the SM is removed.

²with negligible mass with respects the mass scale of particle physics

Contributions to stationary solutions have been studied by evaluating fermion matrix elements, see ref. [2], which lead to potentials with a coupling between two (2g) and three boson (3g) fields $V_{2g}(r)$ and $V_{3g}(r)$. The potential $V_{2g}(r)$ has been identified with the confinement potential in hadrons, whereas $V_{3g}(r)$ can be considered as boson-exchange potential coupled to two-boson fields. In r-space these potentials are given in the form

$$V_{2g}(r) = \frac{\alpha^2 \tilde{m} \langle r_{w'_s}^2 \rangle}{2} \left(\frac{d^2 w'_s(r)}{dr^2} + \frac{2}{r} \frac{dw'_s(r)}{dr} \right) \frac{1}{w'_s(r)} . \quad (2)$$

and

$$V_{3g}^{s,v}(r) = -\frac{\alpha^3}{\tilde{m}\hbar} \int dr' w_{s,v}^2(r') v_v(r-r') . \quad (3)$$

These potentials involve bosonic (quasi) wave functions³ $w_s(r)$ and $w_v(r)$ of scalar and vector character, respectively, whereas $v_v(q)$ can be regarded as boson-exchange interaction with a structure $v_v(q) \sim w_v(q)$. The self-consistent wave function $w_s(r)$ is of the form

$$w_s(r) = w_{s_0} \exp\{-(r/b)^\kappa\} , \quad (4)$$

with a parameter b different for potential $V_{2g}(r)$ and $V_{3g}(r)$. The wave function $w_v(r)$ is related to a p-wave density

$$w_v^2(\vec{r}) = w_v^2(r) Y_{1,m}(\theta, \Phi) = w_{v_0}^2 (1 + \beta R d/dr) w_s^2(r) Y_{1,m}(\theta, \Phi) , \quad (5)$$

where βR is determined from the condition $\langle r_{w_v^2} \rangle = 0$ (invariance to translational motion).

The different parameters are constrained by geometrical boundary conditions, mass, energy and momentum relations. Geometric boundary conditions arise from the requirement that for the fundamental 1^- state of the system the interaction should take place inside the bound state volume. This leads to a similar form of the fermionic and bosonic wave functions $\psi_{(1-)}(r) \sim w_s(r)$ and two further conditions [2]

$$c_1 w_s^2(r) \sim |V_{3g}^v(r)| \quad (6)$$

and

$$c_2 w_s^2(r) = |V_{3g}^s(r)| + |V_{3g}^v(r)| + V_{2g}'(r) , \quad (7)$$

where $V_{2g}'(r) \sim (\alpha^2/2\tilde{m})w_s'^2(r)$.

³which are in fact interactions, leading to boson (quasi) densities $w_{s,v}^2(q)$ with dimension $[GeV]^2$.

The mass of the system is defined by

$$M_n = -E_{3g}^n + E_{2g}^n , \quad (8)$$

where E_{3g}^n are negative binding energies in $V_{3g}^s(r)$ or $V_{3g}^v(r)$ and E_{2g}^n positive binding energies in $V_{2g}(r)$ (for $n = 1$ the index n is dropped). Further, there is a relation between the mass parameter \tilde{m} and the binding energies E_{2g} and E_{3g}

$$\frac{1}{2} E_{2g} < \tilde{m} < \frac{1}{4} |E_{3g}| , \quad (9)$$

and finally a relation between the mass of the fundamental state to the average momentum $\langle q \rangle = \int q dq w_s^2(q) / \int dq w_s^2(q)$

$$M = \langle q \rangle . \quad (10)$$

Altogether there are five constraints (6) - (10), by which **all** five open parameters in eqs. (2) - (4) are determined within limited uncertainties.

Concerning the fermionic wave functions $\psi(r)$, scalar and vector coupling can give rise to 1^- and 0^+ states. In combination with the two bosonic potentials $V_{3g}^s(r)$ and $V_{3g}^v(r)$, four states are expected, two vector 1^- and two scalar 0^+ states. For the two vector states the wave function $\psi_{(1-)}(r) \sim w_s(r)$ is dominantly a s-wave, whereas the two scalar states require a p-wave structure of the wave function $\psi_{(0+)}(r)$ with the details discussed below. In calculating matrix elements and binding energies for these states, angular momentum and spin coupling coefficients $\langle q\bar{q} | L | 1^- \rangle$ (with $L=0$ and 2) and $\langle q\bar{q} | L | 0^+ \rangle$ (with $L=1$) have been taken into account as well as the corresponding components of the multipole-expansion of the interaction $v_v(r) = \sum v_v^L(r)$. These are given by $v_v^L(r) = \langle q\bar{q} | L | 0^+, 1^- \rangle^2 v_v(r)$, since $v_v(r)$ couples only to $q\bar{q}$ states.

The above formalism has been applied to $q\bar{q}$ states in the “top”-mass region. In this mass region two states observed experimentally have been interpreted in conflict with the present approach. This is $Z(91.2 \text{ GeV})$, which has been interpreted as one of the heavy gauge bosons of the weak interaction, the other is the recently discovered scalar state [3] with a mass of 126 GeV , tentatively interpreted as the long sought SM Higgs-boson. Both interpretations are not compatible with our results, in which the mass problem of the SM is solved and therefore the Higgs-mechanism [4] is not needed. But without this mechanism the present form of the weak interaction theory is not gauge invariant.

First some comments are made on weak interactions and the structure of leptons. One should realise that hadrons decay to leptons and vice versa. Further, the states $W^\pm(80.4 \text{ GeV})$ and $Z(91.2 \text{ GeV})$, regarded so far as gauge bosons of the weak interaction, show a branching of about 70 % into hadrons, which does not exclude an interpretation of these states as mesonic states. Together with the fact that flavour is observed in hadrons and leptons, this points to a basically similar structure of hadrons and leptons, with the important difference that leptons are much smaller in size than hadrons (the electron radius has been found to be $\leq 10^{-3} \text{ fm}$) and couple by a weak interaction. In the quantonium model [6] (in which leptons are also described as relativistic bound states of three quanton structure) these facts are understood: The large difference to hadrons is due to a dominant spin coupling between quantons and massless gauge bosons, which is many orders of magnitude smaller than charge coupling, see the discussion in ref. [6]. A clear consequence of this model is that heavy gauge bosons of the weak interaction should not exist.

Different flavour systems are characterized in the present approach by a different slope parameter b only. Therefore, all flavour systems should have a rather similar structure, with a low mass 1^- state and a high mass vector state, expected to decay to two mesons or baryons. There are differences, e.g. in the strength of the potentials $V_{2g}(r)$ and $V_{3g}(r)$, with a dominance of $V_{3g}(r)$ for heavy systems. The lightest flavour system has a low lying vector state at the 2π threshold, for the second system this is the $\omega(782)$ meson. The corresponding high mass states are expected to decay into two pions or light baryons. The third system corresponds to strangeness with the $\Phi(1020)$ vector meson and a high lying state, which should decay dominantly into two kaons or strange baryons. The forth and fifth systems correspond to charm and beauty with the $J/\psi(3097)$ and $\Upsilon(9460)$ vector states and high mass states, which decay to two D- and B-mesons, respectively. A similar structure is also expected for the top system with a low mass vector state and a “top”-state ($t\bar{t}$ in the quark model), which decays to two “single-top” states [5] (interpreted in the quark picture as single top-quark coupled to a lighter antiquark).

By adjusting the five parameters b , b' , κ , \tilde{m} and α to the five constraints discussed above, the potentials $V_{3g}(r)$ and $V_{2g}(r)$ are well determined. However, in the present case the bound for \tilde{m} in eq. (9) is rather wide, giving rise to significant ambiguities between \tilde{m} and α . These could be reduced to a large extent, if bound states in the confinement potential

could be observed. Results on the radial dependence of densities and potentials are given in fig. 1. In the upper part the interaction $v_v(r)$ is given by the solid line. Compared to the Coulomb potential there are no divergencies for $r \rightarrow 0$ and ∞ , consistent with the requirement of a finite theory.

In the middle part a comparison of the density $w_s^2(r)$ (dot-dashed line) with the potentials $V_{3g}^s(r)$ (dashed line) and $V_{3g}^v(r)$ (solid line) is made. We see that condition (6) for the vector potential is well fulfilled at larger radii. In the lower part the scalar two-boson density $w_s^2(r)$ (upper dot-dashed line) is compared to the sum of all potentials. A smaller slope parameter b' meets the boundary condition (7), showing a good self-consistency of the present approach. Qualitatively, a similar behaviour is observed as for light flavour systems discussed in ref. [2].

In fig. 2 the potential $V_{2g}(r)$ is given, which has the typical form of the 'confinement' potential $V_{conf} = -\alpha/r + l \cdot r$ deduced from potential models. Excited states in this potential should give rise to a spectrum of 1^- states similar to those observed for charmonium and bottonium. In the lower part the Fourier transform of $V_{2g}(r)$ is shown, which shows a rapid fall-off, which is directly related to the width of the fundamental state, see ref. [2]. Within the used numerical resolution, the rapid fall-off gives rise to fluctuations in the Fourier transformation (dot-dashed line), which may be avoided by more involved techniques. Here the distribution is fitted by a Gaussian form (solid line), which should be a reasonable approximation.

A first important result is that the expected low mass 1^- vector state is found with a mass of about 90 GeV, consistent with the mass of $Z(91.2 \text{ GeV})$. This may be taken as strong support for the quantonium model description [6] of the weak interaction, in which heavy gauge bosons do not exist. Concerning $W^\pm(80.4 \text{ GeV})$, these states may be considered as mesonic 1^- states of isovector structure, with a relation to $Z(91.2 \text{ GeV})$ qualitatively similar to that of the vector mesons $\rho^\pm(770)$ to $\omega(782)$.

In the further analysis only parameters were used, which reproduce the mass of $Z(91.2 \text{ GeV})$, see table 1. A high mass vector state is obtained with a mass of 372 GeV in agreement with the "top"-state observed experimentally (plus a small extra mass Δ), which decays into two "single-top" states with masses of about 175 GeV, see ref. [5].

Now the possibility to generate scalar (0^+) states is discussed. For these states the

Table 1: Results for the “top”-system ($M(V_{3g}^s)$ fixed to 91 GeV) in comparison with the data [1]. The mass of the new scalar state is taken from ref. [3]. Masses are given in GeV, b and b' in fm, and mean radius squares in fm². For the low mass vector state $E_{2g}=0.6$ GeV and $E_{3g}=-90.6$ GeV. Solutions for $V_{2g}(r)$ yield excited 1^- states with masses of 97 GeV, 102 and 108 GeV, but with large uncertainties.

System	state	$M(V_{3g}^s)$ $M(V_{3g}^v)$			M_{exp}^{low}	M_{exp}^{high}
vector (1^-)	Z , “top”	91	372		91.2 ± 0.1	$2 \cdot 175 \pm 10 + \Delta$
scalar (0^+)	“new”	33	126		–	126 ± 0.8
b	b'	κ	\tilde{m}	α	$\langle r_{w_s}^2 \rangle$	$\langle r_{w'_s}^2 \rangle$
$3.3 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$	1.38	0.40	0.384	$0.84 \cdot 10^{-5}$	$0.58 \cdot 10^{-5}$

fermionic wave function should be a p-wave of a form

$$\psi_{0^+}(r) = c_N \psi_{1^-}(r) + \beta R \frac{d\psi_{1^-}(r)}{dr} \quad (11)$$

with the condition $\langle r_{\psi_{0^+}} \rangle = 0$ (translational invariance) and correctly normalised. By changing βR it was found that indeed such a wave function can be constructed for the top-system, see fig. 3, indicating that such states should exist. Since there are two boson-exchange potentials $V_{3g}^s(r)$ and $V_{3g}^v(r)$, this gives rise to a low and a high mass scalar state with masses of 33 GeV and 126 GeV. The mass of the heavier 0^+ state is in excellent agreement with the mass of the recently discovered [3] scalar state (suspected to be the Higgs-boson). The low mass scalar state should be observable in high energy experiments and can serve as a consistency test of the present model.

In fig. 3 a comparison of the different fermion and boson s- and p-wave densities is made, which shows that the bosonic p-wave density (dot-dashed line) has a structure rather different from the fermionic p-wave density. This is due to the fact that translational invariance is required for the bosonic density $w_v^2(r)$ to get a radially less extended potential $V_{3g}^v(r)$, which matches $w_s^2(r)$, see eq. (6).

The complete flavour-system includes also excited states in the confinement potential $V_{2g}(r)$. For lighter systems, see e.g. charmonium and bottonium, these are the states, which can be investigated easily. Due to the large ambiguity between \tilde{m} and α for the top-system, the first three excited 1^- states have masses between 93 and 98 GeV, 94

and 103 GeV as well as 95 and 110 GeV, dependent on the strength of the confinement potential. It would be of large value, if these states could be detected.

Finally, mass distributions extracted from the Fourier transform of the potentials $V_{2g}(r)$ and $V_{3g}(r)$ are given in fig. 4 (details are given in ref. [2]). Similar to light flavour systems the boson-exchange potential $V_{3g}(r)$ gives rise to wide structures, which are given by dot-dashed lines. In contrast, narrow peaks are generated from the Fourier transformed confinement potential $V_{2g}(r)$, see fig. 2. So, only the confinement potential allows to observe narrow $q\bar{q}$ states. For the vector state at 91 GeV the extracted width of the distribution is 18 GeV, whereas the experimental width of $Z(91.2 \text{ GeV})$ is about 2 GeV. This difference indicates a delayed decay, but with a significantly shorter lifetime then found for the lighter flavour states $J/\psi(3097)$ and $\Upsilon(9460)$. This may indicate a decrease of stability for very heavy flavour systems.

In summary, a self-consistent solution of the relativistic bound state problem has been applied to the description of top-states. Two $q\bar{q}$ vector states have been found, which are in agreement with states observed experimentally, one identified with $Z(91.2 \text{ GeV})$, the other with the “top”-state ($t\bar{t}$ in the quark picture). Further, two scalar states are obtained, one with a mass in striking agreement with the recently detected scalar state at 126 GeV. The other has a mass of 33 GeV and should be detected in high energy experiments. This can be taken as important test of the present model.

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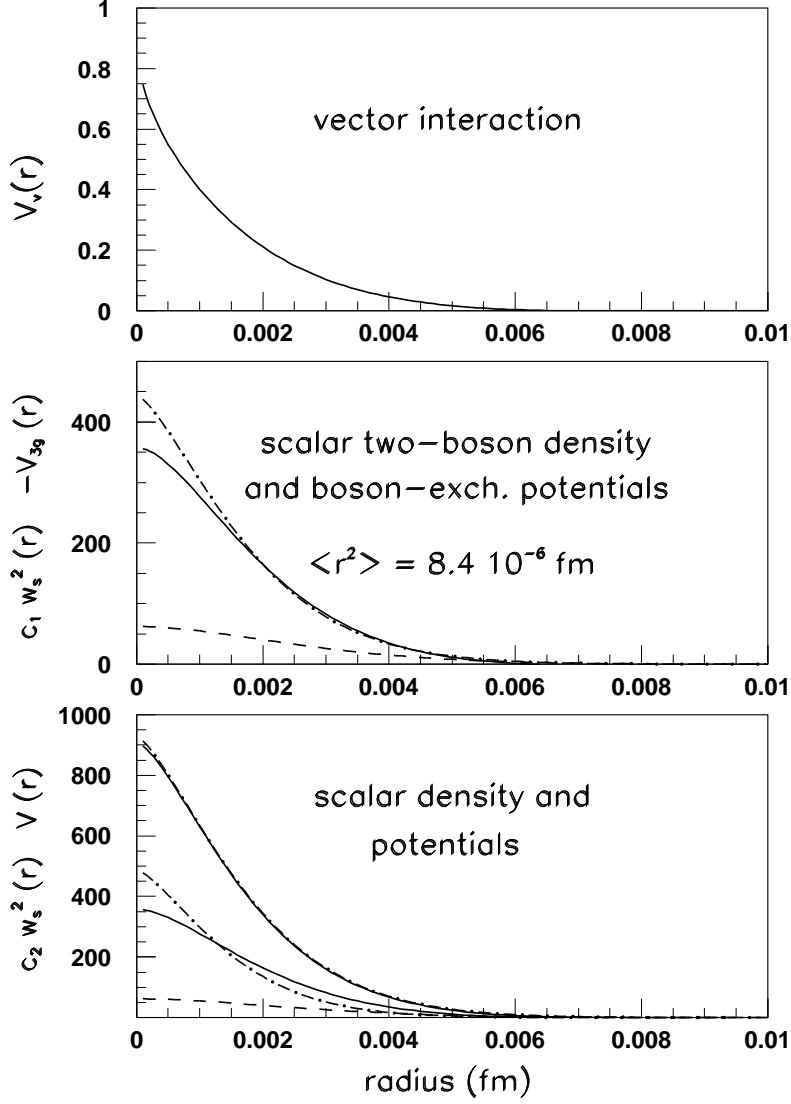


Figure 1: Self-consistent solution for vector $q\bar{q}$ states in the “top”-mass region. Upper part: Interaction $w_v(r)$ given by solid line. Middle part: Bosonic density $w_s^2(r)$ and potential $|V_{3g}^v(r)|$ given by the overlapping dot-dashed and solid lines, matched by the condition (6), and $|V_{3g}^s(r)|$ shown by dashed line. Lower part: Potentials $V_{2g}'(r)$ (lower dot-dashed line), $|V_{3g}^s(r)|$ (dashed line), $|V_{3g}^v(r)|$ (lower solid line) and sum (solid line) in comparison with $w_s^2(r)$ (upper dot-dashed line), which shows a good fulfillment of condition (7).

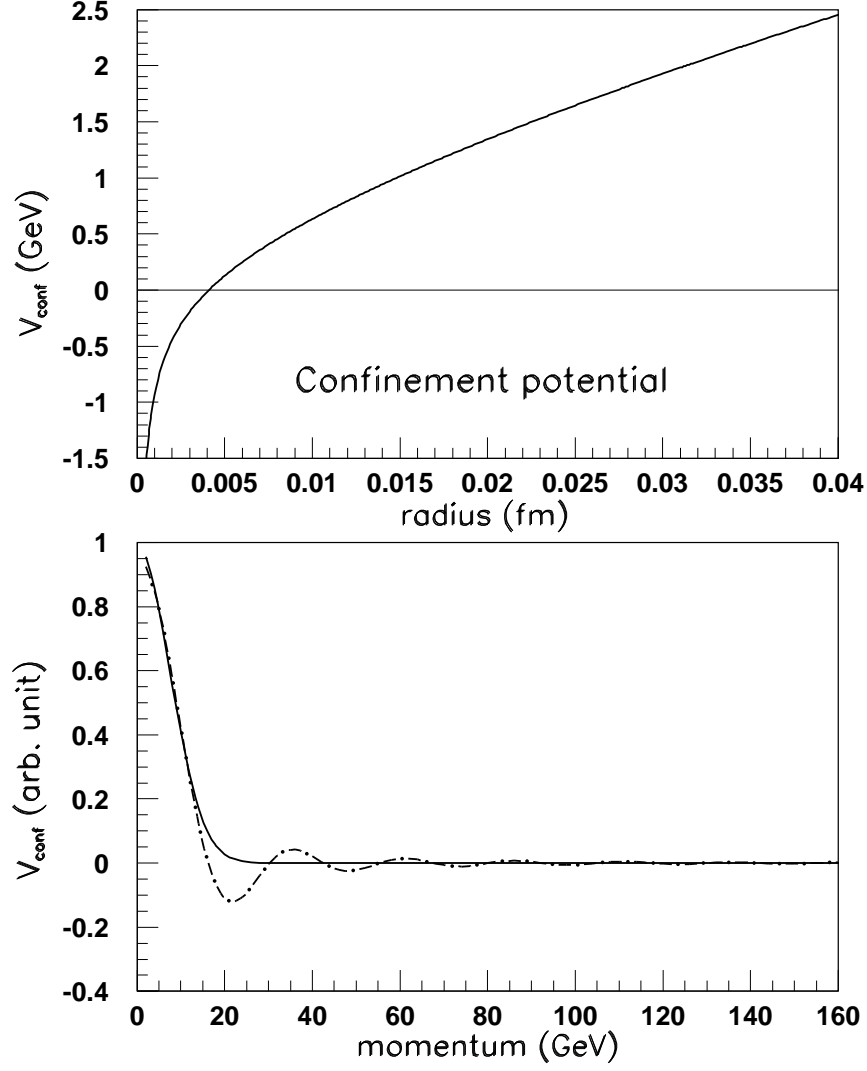


Figure 2: Confinement potential $V_{2g}(r)$ (upper part) and Fourier transform (lower part) given by dot-dashed line. The solid line corresponds to a Gaussian approximation.

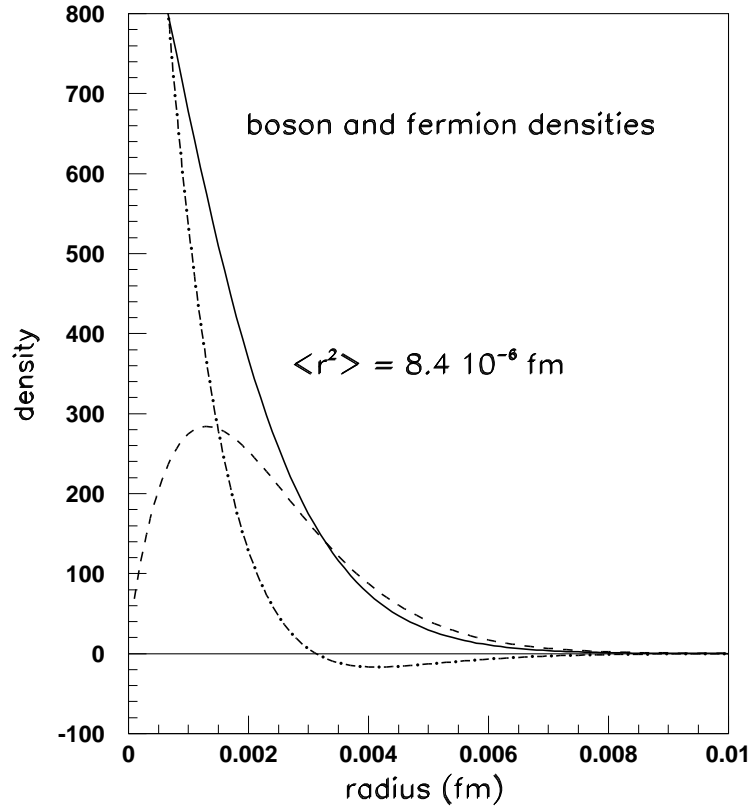


Figure 3: Fermion and boson densities used to calculate vector and scalar states. The s-wave densities $\psi_{(1-)}^2(r) \sim w_s^2(r)$ are given by the solid line, the p-wave densities $\psi_{(0+)}^2(r)$ by dashed and $w_v^2(r)$ by dot-dashed line.

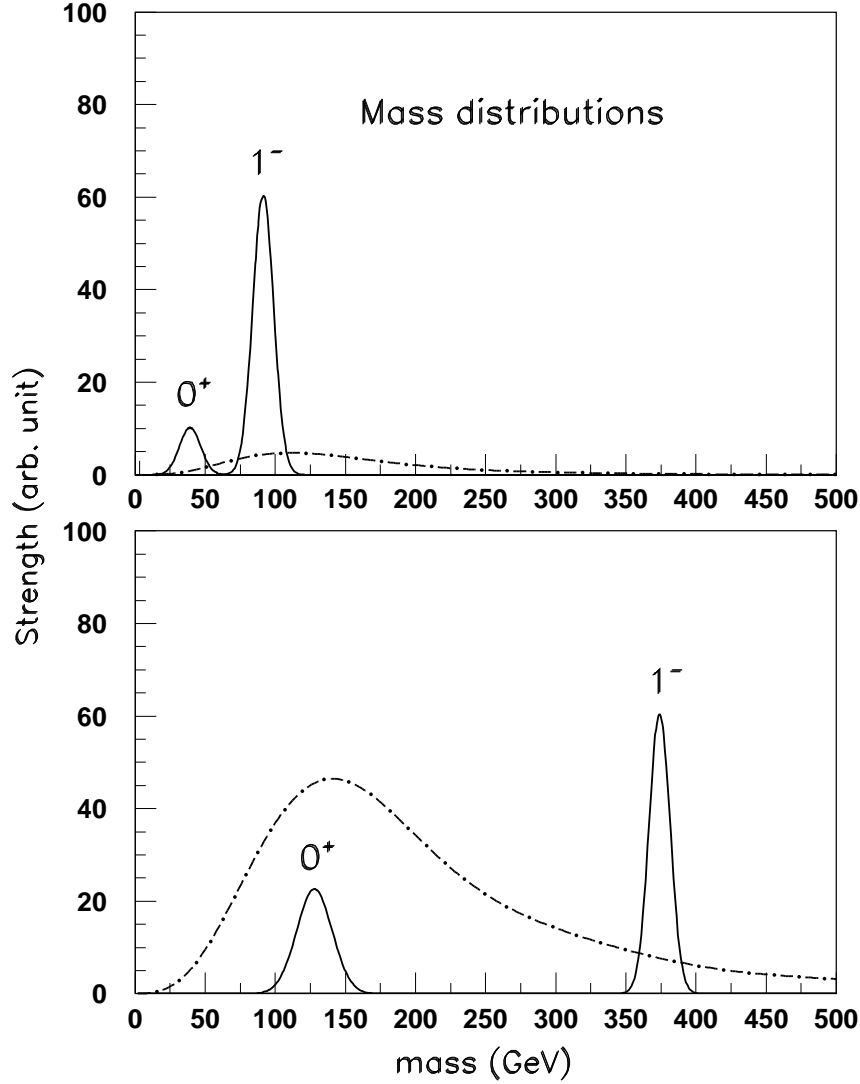


Figure 4: Mass distributions for vector and scalar states (solutions for $V_{3g}^s(r)$ and $V_{3g}^v(r)$ in the upper and lower part, respectively). The pronounced peaks given by solid lines are due to the Fourier transform of $V_{2g}(r)$, whereas that of $V_{3g}(r)$ gives rise to the wide dot-dashed distributions. The narrow low mass 1^- state is identified with $Z(91.2 \text{ GeV})$ and shows properties of a delayed decay (experimental width smaller than calculated). The high mass vector state is consistent with the “top”-state found experimentally (two times “single-top” mass $+\Delta$). 0^+ states are found with masses of 33 GeV and 126 GeV, the latter identified with the new scalar state found in Atlas and CMS data [3].